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RESEARCH MEMORANDUM

ROCKET-ENGINE THROTTLING

By William A. Tomazic

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

The performance and operating characteristics of two variable-thrust injectors were investigated over a wide thrust range using mixed oxides of nitrogen and ammonia. Specific impulse, characteristic velocity, thrust coefficient, and over-all efficiency (percent of theoretical specific impulse achieved) are presented as functions of thrust. Thrust is also shown as a function of chamber pressure.

A maximum thrust range of 12 during one run was obtained with a triplet impinging-jet injector. Specific impulse varied from 238 pound-seconds per pound at full thrust (96 percent of the theoretical peak at full thrust) to 123 pound-seconds per pound at 1/10 thrust (72 percent of the theoretical peak at 1/10 thrust).

A maximum throttling range of 18.5 was obtained during one run with a swirl-cup injector. Specific impulse varied from 222 pound-seconds per pound at full thrust (90 percent of the theoretical peak at full thrust) to 116 pound-seconds per pound at 1/10 thrust (69 percent of the theoretical maximum at 1/10 thrust).

INTRODUCTION

Controlled variation of thrust is of interest in manned aircraft power plants, missile-guidance programming, and ducted rocket engines. Simple thrust control, smooth combustion, and high specific impulse throughout the thrust range are desirable features in such applications. High specific impulse requires the maintenance of good mixture preparation and high nozzle pressure ratios throughout the thrust range. To achieve both of these, throttling of liquid flow at the injector and of gas flow at the engine throat are required.

The work reported herein is concerned only with liquid throttling at the injector. The injectors used were developed from the two most promising constant-thrust types tested (ref. 1). With a triplet impinging-jet injector, flow throttling was achieved by changing the number of operative triplet sets with pistons in the flow passages. With a swirl-cup injector, flow was varied by a single piston controlling the orifice area. This type of injection and control had been used previously (ref. 2).

The triplet injector was tested at chamber pressures from 47 to 457 pounds per square inch absolute and at thrusts from 96 to 1710 pounds. The swirl-cup injector was tested at chamber pressures from 42 to 435 pounds per square inch absolute and at thrusts from 86 to 1587 pounds.

Experimental specific impulse, characteristic velocity, thrust coefficient, and over-all efficiency (percent of theoretical specific impulse achieved) are shown as functions of thrust. Thrust is also presented as a function of chamber pressure.

APPARATUS

Propellants and Flow System

The oxidant was mixed oxides of nitrogen, which consisted of 70 to 72 percent nitrogen tetroxide and 28 to 30 percent nitric oxide. The fuel was liquid anhydrous ammonia. Both were obtained as liquids in commercial cylinders.

The propellants were fed to the engine from helium-pressurized tanks, with the flow rates controlled by tank pressures. Firing operations were accomplished with remotely controlled valves. A chamber was provided between the fuel-control valve and the engine to hold the lithium used to obtain spontaneous ignition (ref. 3). All components of both flow systems were of stainless steel.

Engine and Mounting

The engine (fig. 1) was a water-cooled unit with a 4-inch chamber diameter designed for 1000-pound thrust at a chamber pressure of 300 pounds per square inch absolute. The engine was mounted on a movable stand supported by two steel flexure plates perpendicular to it. The stand was inclined downward at an angle of 30°.

Injectors

Triplet impinging-jet injector. - The triplet impinging-jet injector is shown in figure 2. Six groups of 10 triplet sets each were arranged in two parallel rows across the injector face. Control pistons under the injector face, moved by a pneumatic valve actuator, varied the number of triplet sets open. The control pistons were designed to make the same change in each of the six groups simultaneously. Of the 60 triplet sets, 54 had 0.047-inch-diameter fuel holes and 0.037-inch-diameter oxidant holes. The other six sets had 0.033-inch-diameter fuel holes and 0.028-inch-diameter oxidant holes. These six sets operating alone gave the minimum flow.

Swirl-cup injector. - The swirl-cup injector (fig. 3) had two fuel and two oxidant entries arranged alternately about the cup 90° apart. The entry holes were tangent to the circumference of the cup and 10° from normal to the axis pointing out of the cup. A movable piston formed the bottom of the cup. The piston was moved by a pneumatic valve actuator to change the orifice area in order to vary the flow into the cup. A high-pressure helium purge behind the piston prevented propellants going behind the piston.

Exhaust Duct System

An exhaust duct and burner system was used for runs with the swirl-cup injector to burn the nitrogen dioxide exhausted from the engine. The duct used to channel the exhaust gases from the rocket to the burner was constricted to approximately a 0.12-inch annulus about the rocket nozzle to minimize the induction of air. This burner and duct were not used for testing of the triplet injector.

Instrumentation

Thrust. - Thrust was measured with a calibrated strain gage and recorded on a self-balancing potentiometer. The accuracy of the measurements, including variation of calibration constants and interpretations of chart readings, was approximately ±2 percent. Accuracy, as used herein, indicates approximately 90 percent confidence that any single value is within the error limits specified.

Flow rates. - Turbine-type flowmeters were used for the majority of the tests. The accuracy of flow measurements made with them, including density determinations, was approximately ±1.5 percent. The extreme low flows for the swirl-cup injector (less than 350-lb thrust) were measured by continuous tank weighing, using calibrated strain gages recording on self-balancing potentiometers. The accuracy of the measurements was approximately ±2.5 percent.

Combustion-chamber pressure. - Combustion-chamber pressure was measured by both Bourdon tube-type recorders and variable-resistance-type pressure pickups where output was recorded on an oscillograph. The accuracy of each method was approximately ±1.0 percent.

Temperature. - Copper-constantan thermocouples were used to measure propellant temperature (within $\pm 2^{\circ}$ F) in the flow lines near the turbine-type flowmeters. Determination of propellant densities was within ± 0.5 percent.

PROCEDURE

Both fuel and oxidant were loaded into the cell tanks as liquids from commercial cylinders. Dry high-pressure helium was used to force the propellants from the tank to the engine. The addition of lithium to ammonia in the flow line made the ammonia self-igniting with mixed oxides of nitrogen. Valve openings were timed for an oxidant lead of approximately 0.1 second on start and a comparable override on shutdown. At shutdown, the injector and chamber were purged with helium. Most runs were 4 to 6 seconds in duration. 3900

Experimental specific impulse was calculated from measured values of thrust and propellant flows. The accuracy of the calculated values was approximately ± 3.5 percent with the turbine-type flowmeters and ± 4.5 percent with the weight method. Characteristic velocity was calculated from measured chamber pressure, throat area, and propellant flows. The accuracy was approximately ± 3.0 with the turbine-type flowmeters and ± 4.0 percent with the weight method. Thrust coefficient was obtained from experimental chamber pressure, thrust, and throat area, to an accuracy of approximately ± 3.5 percent.

Performance of the triplet injector was obtained at various thrust levels as a function of the oxidant-fuel ratio. Above half-thrust, peak performance points were distinctly determined to give performance as a function of thrust. Below half-thrust, operating difficulties (e.g., poor mixture-ratio control; see DISCUSSION) prevented a good determination of peak performance at each thrust level. The points given represent the highest performances as measured but are not for optimum mixture-ratio conditions. One point, at a 372-pound thrust, was extrapolated from data for conditions far from the optimum mixture ratio.

With the swirl-cup injector, runs were made at various thrust levels. From these, all the runs in a specified range of oxidant-fuel ratio (1.31 to 2.06) were plotted directly to give performance as a function of thrust.

Theoretical specific impulse as a function of thrust and thrust as a function of chamber pressure were calculated to give a basis of comparison with the experimental data (appendix A).

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RESULTS

The experimental data for the triplet impinging-jet injector are shown in table I and figures 4 and 5. Figure 4 shows specific impulse, characteristic velocity, and thrust coefficient as functions of oxidant-fuel weight ratio for full-thrust operation. The peak specific impulse was 238 pound-seconds per pound at an oxidant-fuel ratio of 1.9, or 96 percent of the theoretical maximum. The characteristic velocity was 5220 feet per second and the thrust coefficient 1.46.

Performance is presented as a function of thrust in figure 5. Specific impulse was 238 pound-seconds per pound at full thrust and 123 pound-seconds per pound, or 72 percent of the theoretical peak, at 1/10 thrust. The largest thrust ratio obtained in a single run was 12. Characteristic velocity dropped from 5220 feet per second at full thrust to 3870 feet per second at 1/10 thrust. Thrust coefficient was 1.46 at full thrust and 0.98 at 1/10 thrust.

The experimental data for the swirl-cup injector are shown in table II and figure 6. Specific impulse, characteristic velocity, and thrust coefficient are presented in figure 6 as functions of thrust. The peak specific impulse was 222 pound-seconds per pound at full thrust, or 90 percent of the theoretical peak. At 1/10 thrust the specific impulse was 116 pound-seconds per pound, or 69 percent of the theoretical value at that thrust. A thrust ratio of 18.5 was obtained during one run with this injector. Characteristic velocity was 4950 feet per second at full thrust and 3840 feet per second at 1/10 thrust. Thrust coefficient ranged from 1.45 at full thrust to 0.93 at 1/10 thrust.

A comparison of the two injectors is shown in figure 7. Over-all efficiency (percent of theoretical specific impulse achieved) is plotted as a function of thrust for both injectors. The triplet injector gave 96 percent of the theoretical maximum efficiency at full thrust, but efficiency dropped steadily as thrust decreased. Although the swirl-cup injector gave only 90 percent of the theoretical peak at full thrust, efficiency did not fall below 90 percent of theoretical maximum until about 1/3 thrust. Below 1/5 thrust, performance of both injectors fell sharply, with the triplet having a small edge.

Thrust as a function of chamber pressure is shown in figure 8. The experimental data follow the theoretical data closely above a chamber pressure of 200 pounds per square inch absolute and fall slightly below it at lower pressures, indicating close agreement with the theoretical nozzle thrust coefficient. Transition between thrust levels was easily accomplished with both injectors. Some rough combustion was encountered with the swirl-cup injector, but it did not hamper operations.

DISCUSSION

The variable triplet injector duplicated the spray pattern of the triplet injector tested in reference 1. Five pistons were added to obtain control of orifice area. The full thrust spray characteristics were good and resulted in good performance. However, when the pistons were used to close off holes to reduce flow, the spray pattern became progressively worse because of excessive leakage around the pistons. The oxidant-fuel ratio also varied with flow change as a result of this leakage. The oxidant leaked much more than the fuel, which was sealed relatively well. The oxidant flow passages forming the protruding portion of the injector face became quite hot during operation, while the recessed fuel passages remained relatively cool (note heat discoloration in fig. 2). This excessive heating evidently warped the oxidant portion of the injector enough to prevent a good seal. The mismatched sprays resulting from the leakage gave successively lower efficiencies as thrust was reduced. Since tank pressures were kept constant, the pressure differential across the injector continuously increased with decreasing thrust. At the extreme low-thrust position (only 1 triplet set open in each group of 10), the greatest leakage through the covered holes occurred. This leakage resulted in both low efficiency and poor mixture-ratio control.

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The variable swirl-cup injector was patterned after the four-entry swirl-cup injector reported in reference 1. However, the orifices were made larger to obtain greater thrust and the cup dimensions were changed slightly. At peak thrust, performance was lower than that obtained in reference 1, evidently because of the changes. Thrust variation was smooth over a wide range and no difficulties were encountered in changing thrust. In contrast to the performance of the triplet, efficiency remained high (90 percent or better) in the entire top two-thirds of the thrust range. The injector flow pattern was not appreciably disrupted until about the 1/3 thrust point when the streams (in water testing) started to leave the cup without having mixed properly. Performance then fell rapidly at lower thrust, as it did with the triplet injector.

The triplet injector could be improved by the addition of a control mechanism that would positively seal off flow. This change would probably result in greater efficiency in the throttled range. Redesign of the cup and propellant entrances could make the performance of the swirl-cup injector comparable to that of the triplet injector.

Over-all performance would be greatly improved for a variable-thrust engine if the gas flow at the throat were also throttled to maintain constant chamber pressure. This, coupled with liquid throttling at the injector as reported herein, would give the most efficient engine. However, structural and cooling problems of a variable throat would probably require considerable research and development.

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SUMMARY OF RESULTS

The performance and operating characteristics of two variable-thrust injectors were investigated over a wide range of thrust using mixed oxides of nitrogen and ammonia. Peak-performance results are summarized as follows:

Injector	Maximum throttling obtained	Thrust, lb	Specific impulse, lb-sec/lb	Percent of theoretical specific impulse	Characteristic velocity, ft/sec	Percent of theoretical characteristic velocity	Thrust coefficient
Triplet impinging-jet	12 to 1	1680 (full thrust)	238	96	5220	96	1.46
		168 (1/10 thrust)	123	72	3870	71	.98
Swirl-cup	18.5 to 1	1585 (full thrust)	222	90	4950	90	1.45
		158.5 (1/10 thrust)	116	69	3840	70	.93

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 21, 1955

APPENDIX A

CALCULATION OF THEORETICAL SPECIFIC IMPULSE

A rocket nozzle operated over a wide range of chamber pressure will offer optimum expansion only at the nozzle design chamber pressure. Above the optimum pressure, the exhaust will be underexpanded; below it, the exhaust will be overexpanded. In addition, when the exit pressure drops far enough (approximately 0.5 of ambient pressure, e.g. ref. 4) the exhaust flow will separate from the nozzle. 3900

For either the underexpanded or the overexpanded case with no separation, the following equation was used to obtain specific impulse as a function of chamber pressure:

$$I = I_{th} + \frac{A_e}{\dot{m}}(P_e - P_a) = I_{th} + \frac{c^*}{g_c}\frac{A_e}{A_t}\left(\frac{P_e}{P_c} - \frac{P_a}{P_c}\right)$$

The theoretical specific impulse for the nozzle design pressure ratio of 20 I_{th} was taken as 238 pound-seconds per pound (ref. 5). Symbols are defined in appendix B. The characteristic velocity was assumed constant over the entire pressure range at 5470 feet per second (ref. 5).

The flow was assumed to separate from the nozzle exit when the exit pressure dropped to 0.5 of the ambient pressure. For the separated case, the following equation was used to calculate specific impulse as a function of chamber pressure:

$$I = I_{s,th} + \frac{1}{\dot{m}}\left[A_s(P_s - P_a) - (A_e - A_s)(P_a - P_x)\right] = I_{s,th}$$
$$+ \frac{c^*}{g_c}\frac{P_a}{P_c}\left[\frac{A_s}{A_t}\left(\frac{P_s}{P_a} - 1\right) - \left(1 - \frac{P_x}{P_a}\right)\left(\frac{A_e}{A_t} - \frac{A_s}{A_t}\right)\right]$$

The maximum theoretical impulse, assuming the nozzle was cut off at the point of separation $I_{s,th}$, was calculated from

$$I_{s,th} = \frac{C_F c^*}{g_c}$$

with c^* assumed constant. C_F was obtained from reference 6 with $\gamma = 1.25$ and a pressure ratio in each case of P_c/P_s (P_s was equal to $0.5P_a$ after separation). The separation area ratio was taken as the ideal area ratio for each separated pressure ratio P_c/P_s from reference 7. The integrated mean pressure over the separated portion of the nozzle P_x was estimated to be 0.9 of the ambient pressure.

This value is accurate for initial separation but becomes less reliable as the separation point approaches the throat.

Thrust was then calculated as a function of chamber pressure using the relation

$$F = \frac{P_c A_t g_c I}{c^*}$$

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The values of I are those previously determined for each P_c. A_t was the throat area of the engine used in the testing. Specific impulse as a function of thrust was then obtained by cross-plotting. It should be noted that the theoretical impulse as presented herein applies only to the particular engine assumed.

APPENDIX B

SYMBOLS

A	area, sq in.
C_F	nozzle thrust coefficient, $\frac{F}{P_c A_t}$
c^*	characteristic velocity, $\frac{P_c A_t g_c}{\dot{m}}$, ft/sec
F	thrust, lb
g_c	conversion factor, 32.2 ft-lb mass/sec^2-lb force
I	specific impulse, $F/\dot{m}$, lb-sec/lb
I_{th}	theoretical maximum specific impulse for nozzle design, lb-sec/lb
$I_{s,th}$	theoretical maximum specific impulse for separated flow assuming the nozzle designed for the point of separation, lb-sec/lb
$\dot{m}$	mass flow of propellants per unit time, lb/sec
P	pressure, lb/sq in. abs
P_x	integrated mean pressure over separated portion of nozzle, lb/sq in. abs
γ	ratio of specific heat at constant pressure to specific heat at constant volume

Subscripts:

a	ambient (sea level)
c	in chamber
e	at nozzle exit
s	at point of flow separation from wall
t	engine throat

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TABLE I. - PERFORMANCE OF TRIPLET IMPINGING-JET INJECTOR

USING MIXED OXIDES OF NITROGEN AND AMMONIA

Thrust, lb	Chamber pressure, lb/sq in. abs	Oxidant-fuel weight ratio	Specific impulse, lb-sec/lb	Characteristic velocity, ft/sec	Thrust coefficient
1542	427	1.47	228	5160	1.43
1825	---	1.51	236	----	----
1605	---	1.65	233	----	----
1710	456	1.66	234	5090	1.48
1666	457	1.78	239	5340	1.44
1688	456	1.85	235	5180	1.46
1695	455	1.88	237	5190	1.47
1695	455	1.90	237	5190	1.47
1682	454	1.93	236	5190	1.46
1684	452	1.98	240	5240	1.47
1660	450	2.01	234	5160	1.46
1690	---	2.15	236	----	----
1298	377	1.60	215	5060	1.37
1384	375	1.77	233	5140	1.46
1245	353	1.78	225	5170	1.40
1415	380	1.82	238	5210	1.47
1350	368	1.83	231	5140	1.45
1410	383	1.91	234	5180	1.46
1403	379	1.92	235	5170	1.46
1370	376	1.92	236	5270	1.44
1407	389	1.97	241	5420	1.43
1339	364	1.98	235	5210	1.45
1233	349	2.17	235	5400	1.40
1345	374	2.22	231	5250	1.42
860	249	1.47	202	4750	1.37
1059	292	1.54	223	4990	1.44
948	272	1.59	206	4790	1.38
970	277	1.70	208	5830	1.39
881	254	1.80	219	5140	1.37
898	260	1.83	216	5090	1.37
975	282	2.24	211	4950	1.37
889	262	2.73	209	5000	1.34
710	211	2.08	197	4760	1.33
716	218	2.35	209	5190	1.30
591	186	2.96	174	4450	1.26

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TABLE I. - Concluded. PERFORMANCE OF TRIPLET IMPINGING-JET INJECTOR USING MIXED OXIDES OF NITROGEN AND AMMONIA

Thrust, lb	Chamber pressure, lb/sq in. abs	Oxidant-fuel weight ratio	Specific impulse, lb-sec/lb	Characteristic velocity, ft/sec	Thrust coefficient
599	186	3.64	168	4230	1.27
396	136	3.29	151	4210	1.15
347	126	3.60	141	4180	1.09
232	89	2.35	149	4660	1.03
227	89	2.67	134	4280	1.01
242	96	3.65	108	3490	1.00
200	86	5.22	106	3720	.92
152	64	4.54	100	3440	.95
141	58	5.04	88	2960	.95
96	47	5.20	87	3460	.81
114	53	5.92	81	3080	.85

TABLE II. - PERFORMANCE OF SWIRL-CUP INJECTOR USING MIXED OXIDES OF NITROGEN AND AMMONIA

Thrust, lb	Chamber pressure, lb/sq in. abs	Oxidant-fuel weight ratio	Specific impulse, lb-sec/lb	Characteristic velocity, ft/sec	Thrust coefficient
1587	435	1.90	221	4910	1.45
1587	433	2.06	224	4960	1.45
----	391	1.59	---	4795	----
1370	383	2.07	217	4930	1.41
1345	372	1.78	226	5080	1.43
1318	366	1.83	220	4970	1.43
1043	291	1.48	221	5000	1.42
975	276	1.39	216	4960	1.40
807	237	1.31	198	4725	1.35
345	122	1.56	180	4920	1.12
176	74	1.57	118	4030	.94
86	42	1.93	72	2840	.81

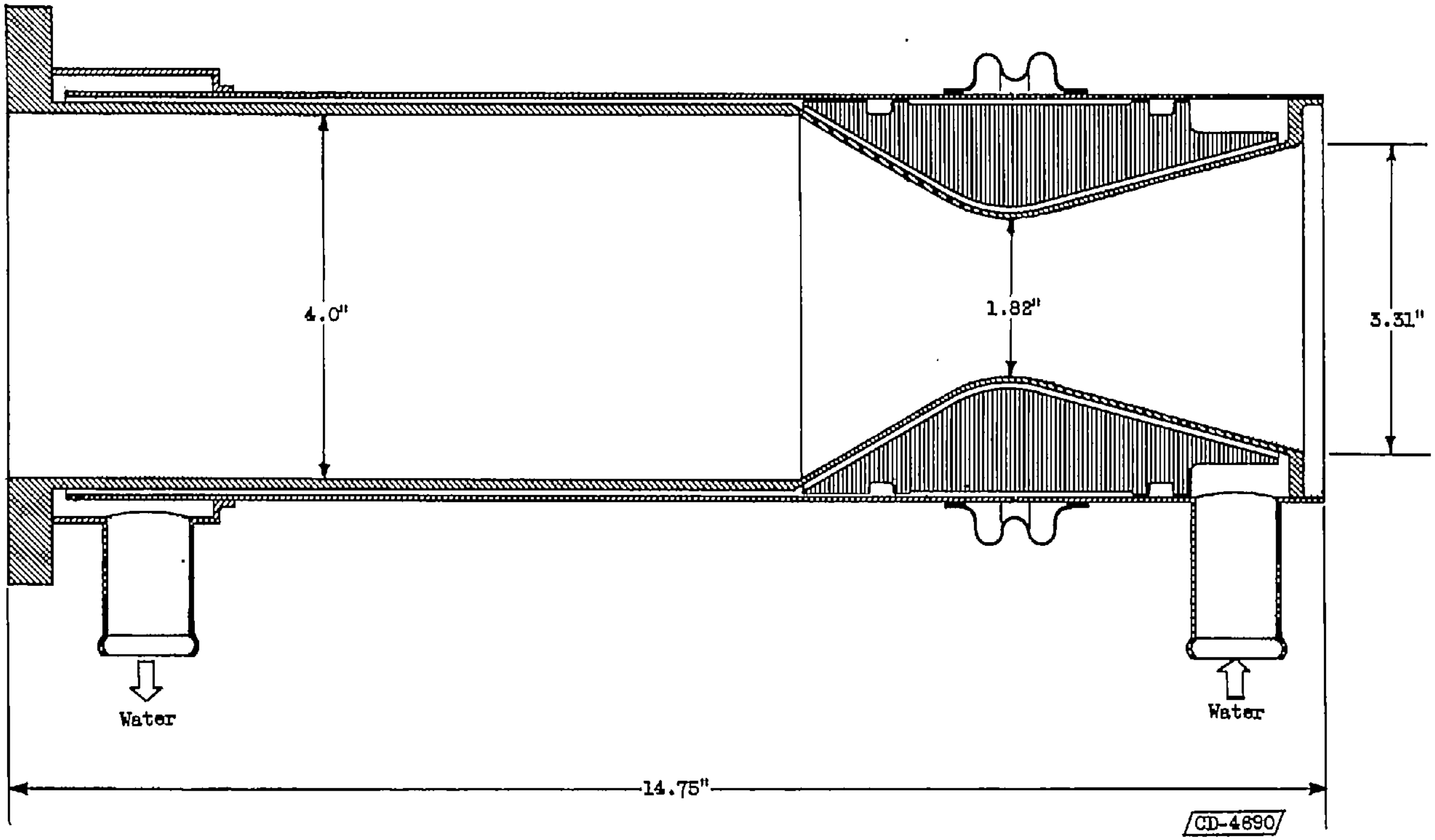

Figure 1. - Water-cooled thrust chamber.

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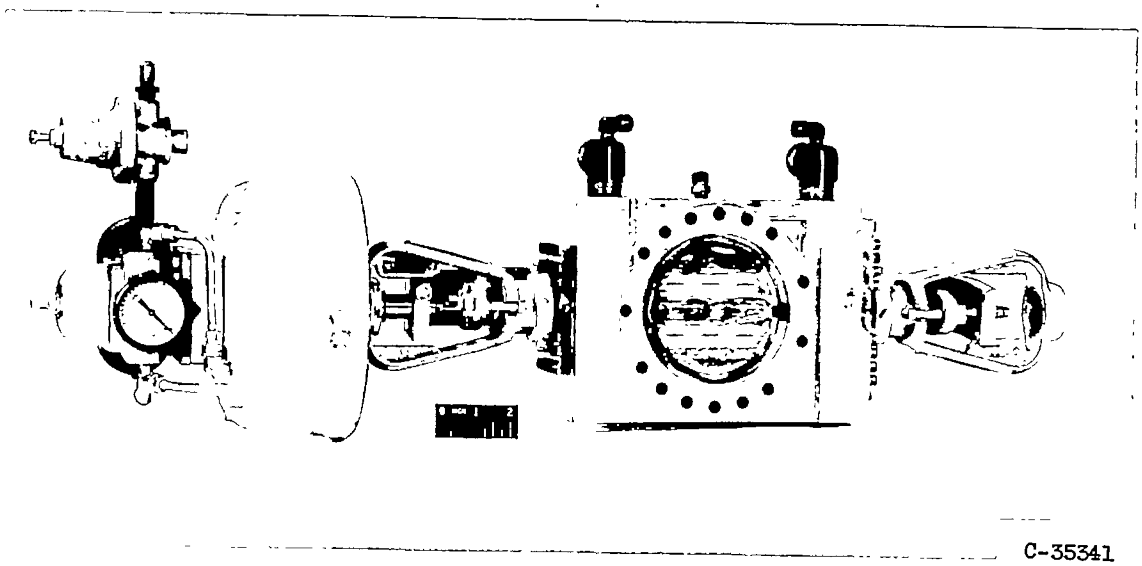

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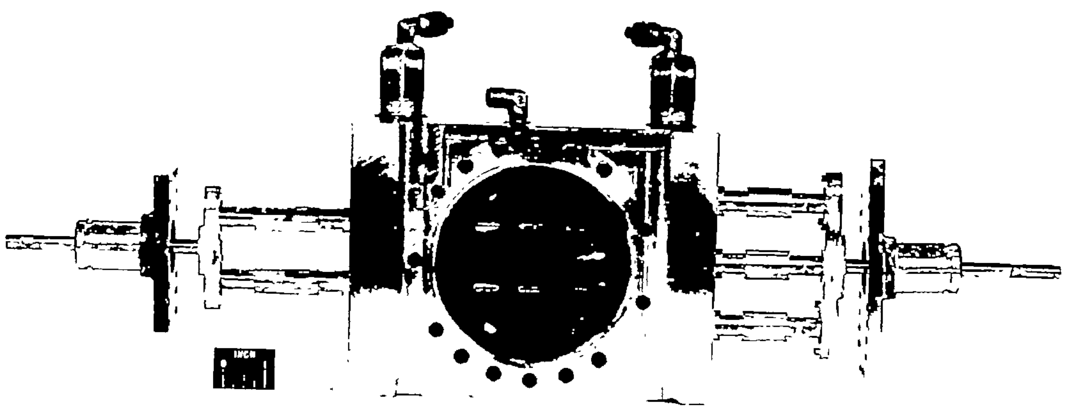
(a) Injector assembly.



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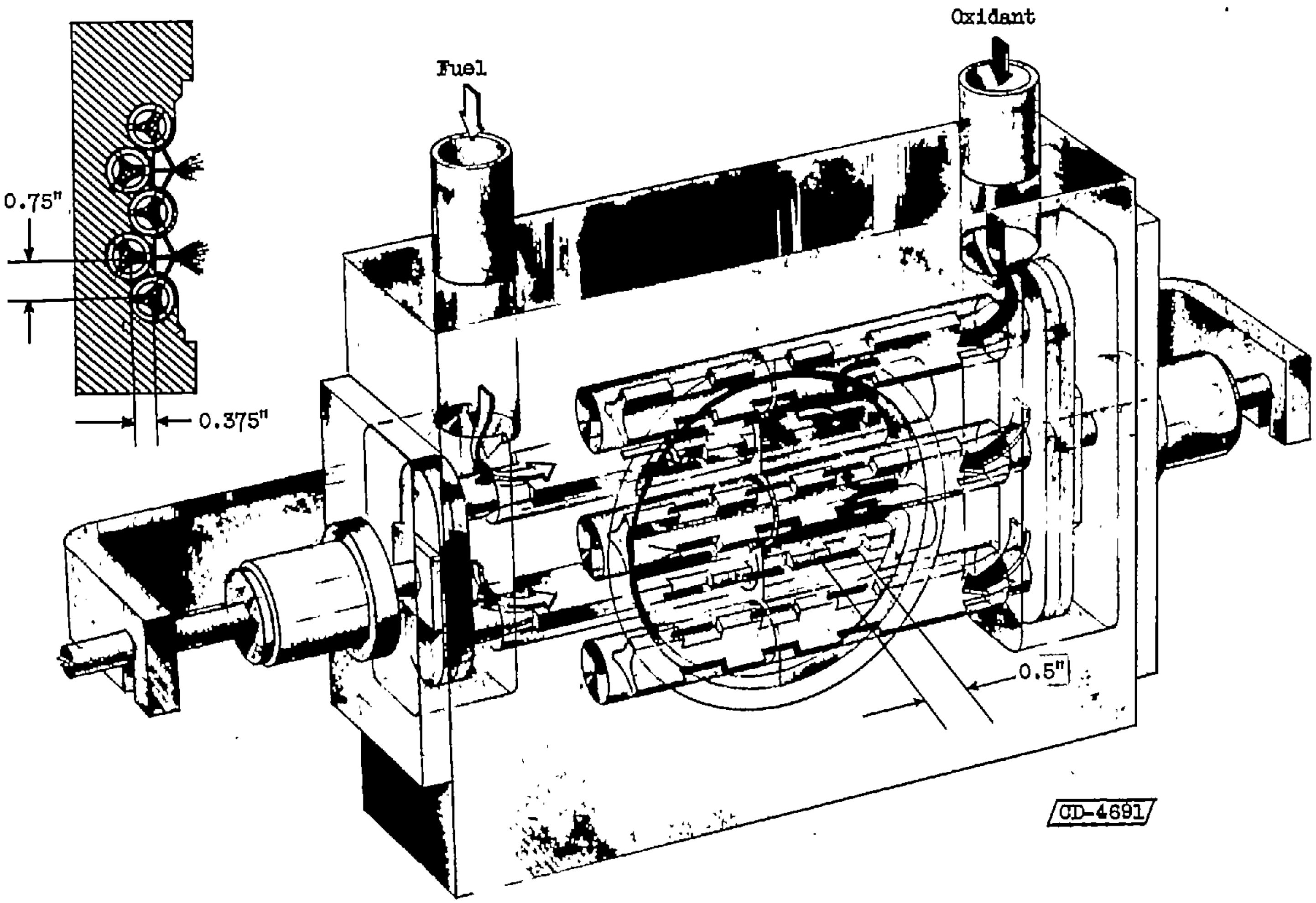
(b) View showing control pistons.

Figure 2. - Triplet impinging-jet injector with flow-control pistons.



(c) Cutaway showing flow paths.

Figure 2. - Concluded. Triplet impinging-jet injector with flow-control pistons.

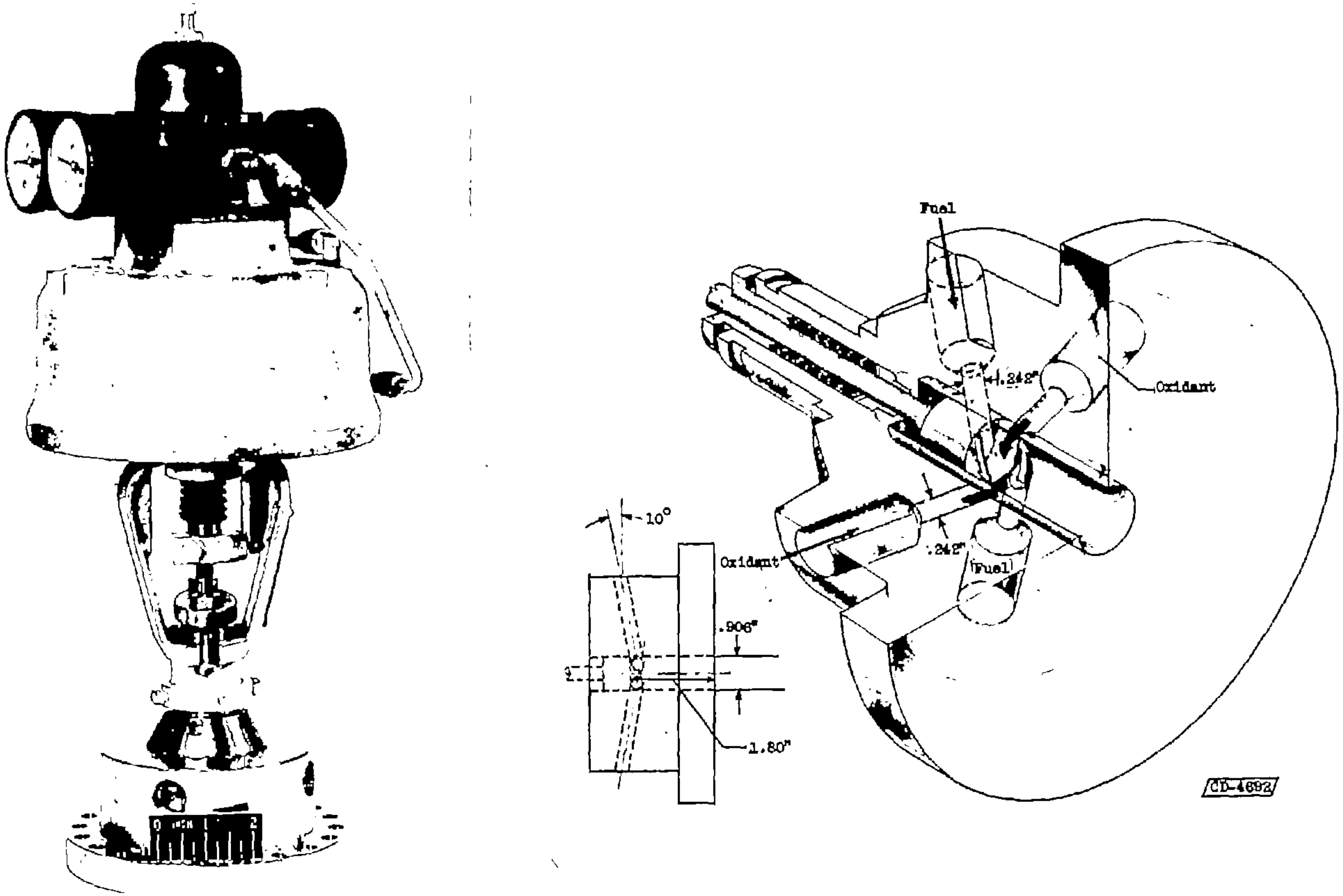


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Figure 3. - Swirl-cup injector with flow-control piston.

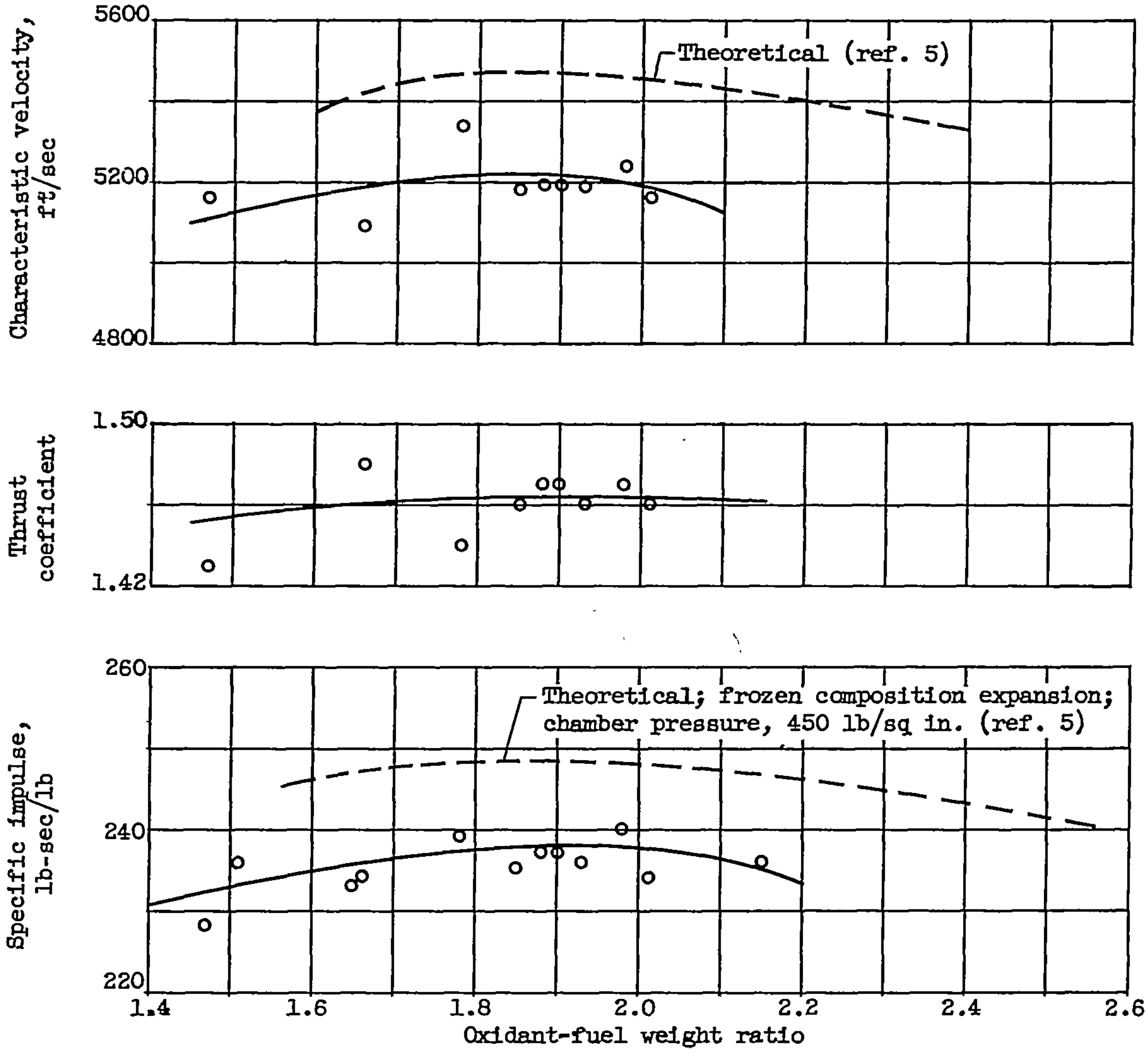

Figure 4. - Theoretical and experimental performance of triplet impinging-jet injector using mixed oxides of nitrogen and ammonia. Thrust, 1680 pounds; chamber pressure, 450 pounds per square inch absolute.

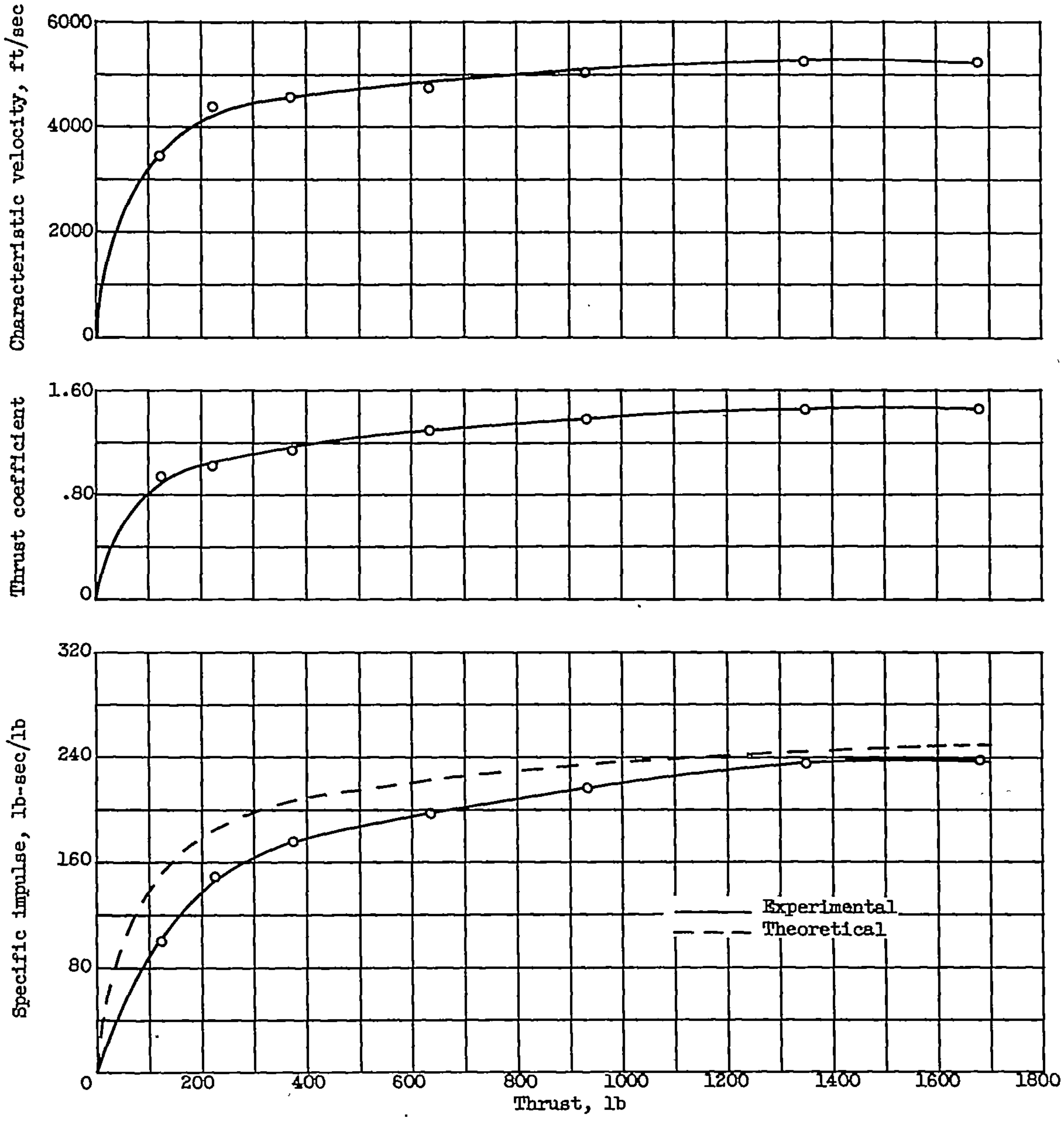

Figure 5. - Performance over wide range of thrust for triplet impinging-jet injector using mixed oxides of nitrogen and ammonia. Nominal full thrust, 1680 pounds.

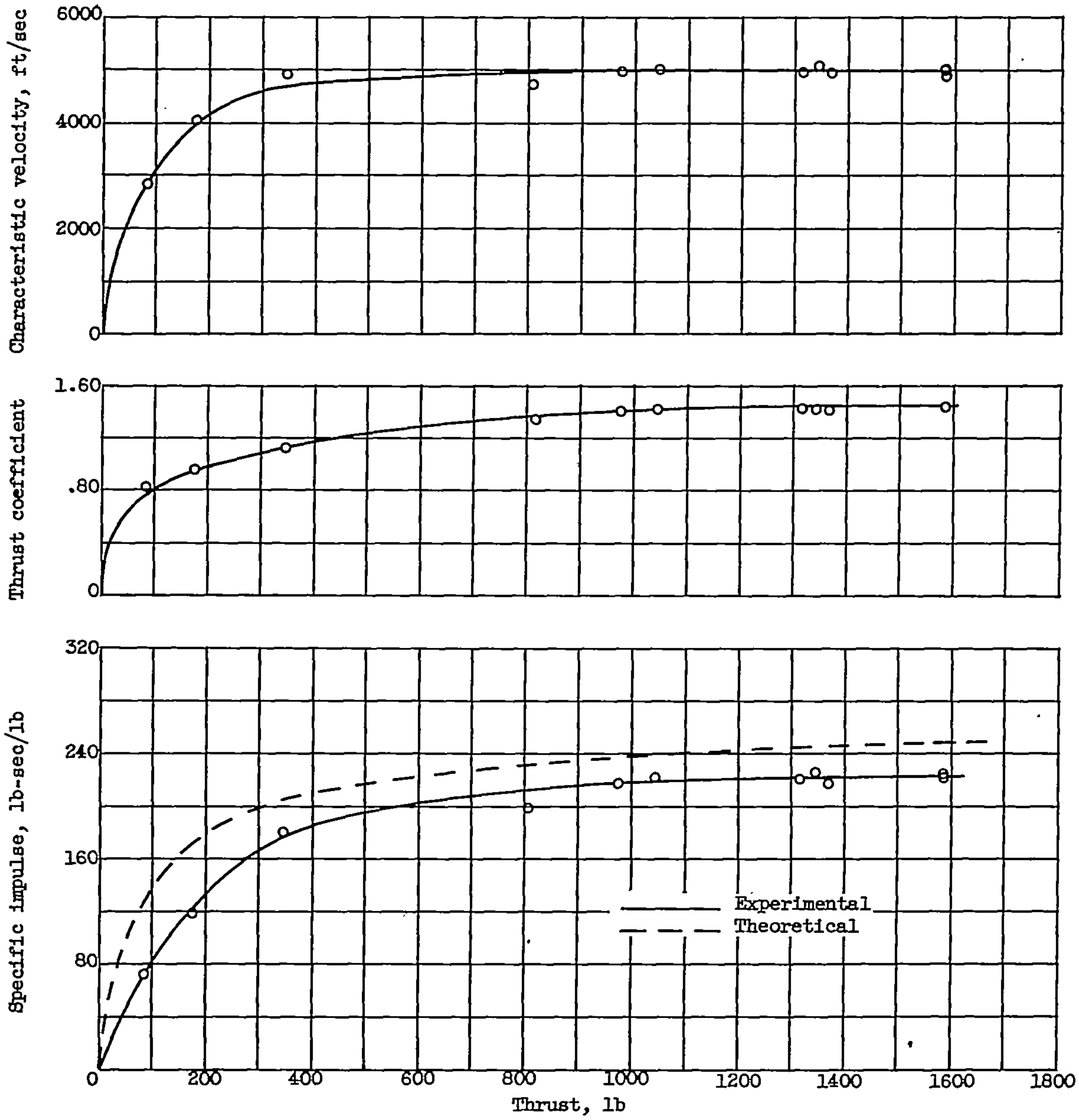

Figure 6. - Performance over wide range of thrust for swirl-cup injector using mixed oxides of nitrogen and ammonia. Nominal full thrust, 1585 pounds.

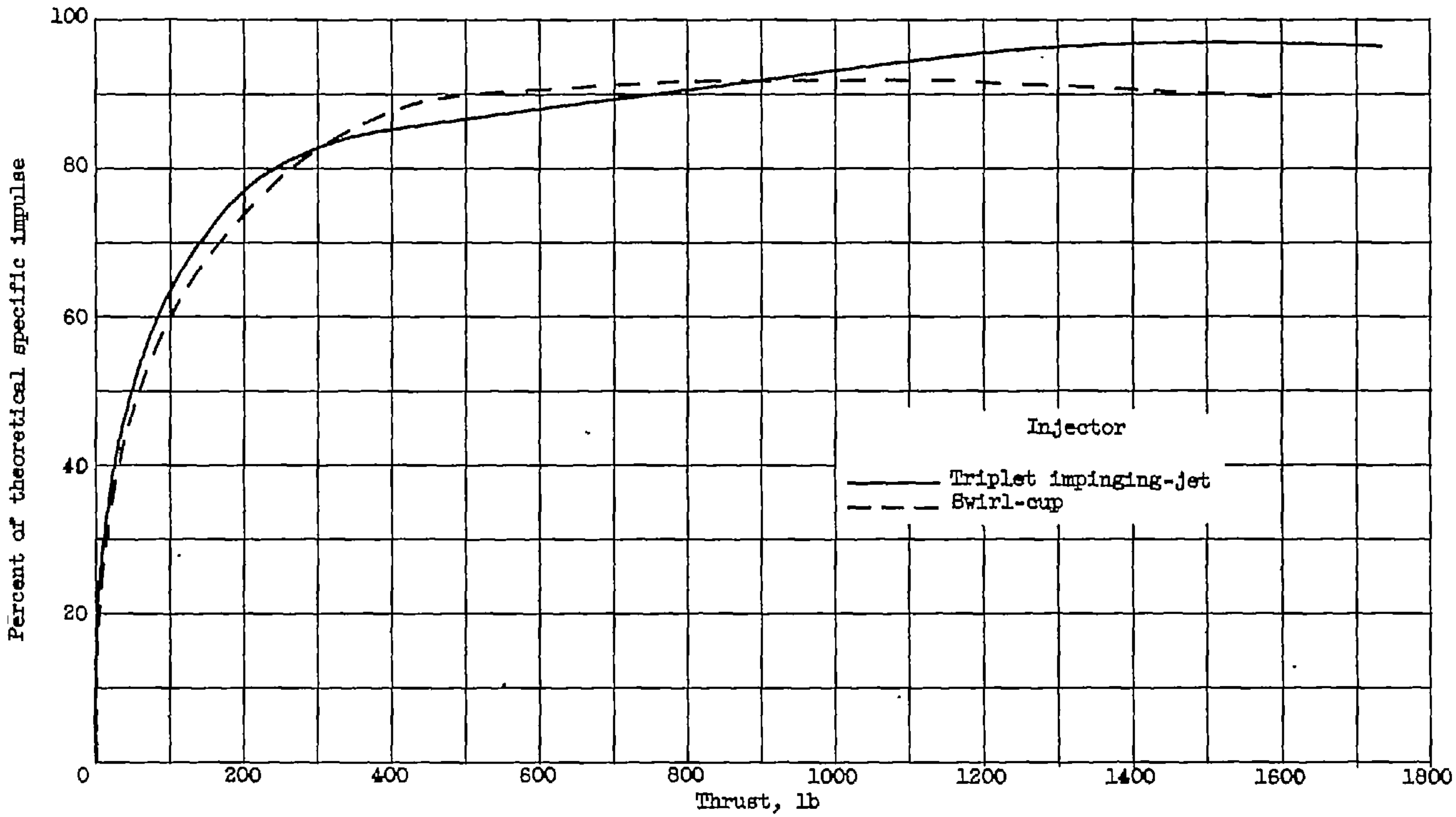

Figure 7. - Percent of theoretical specific impulse as function of thrust for two variable-thrust injectors using mixed oxides of nitrogen and ammonia.

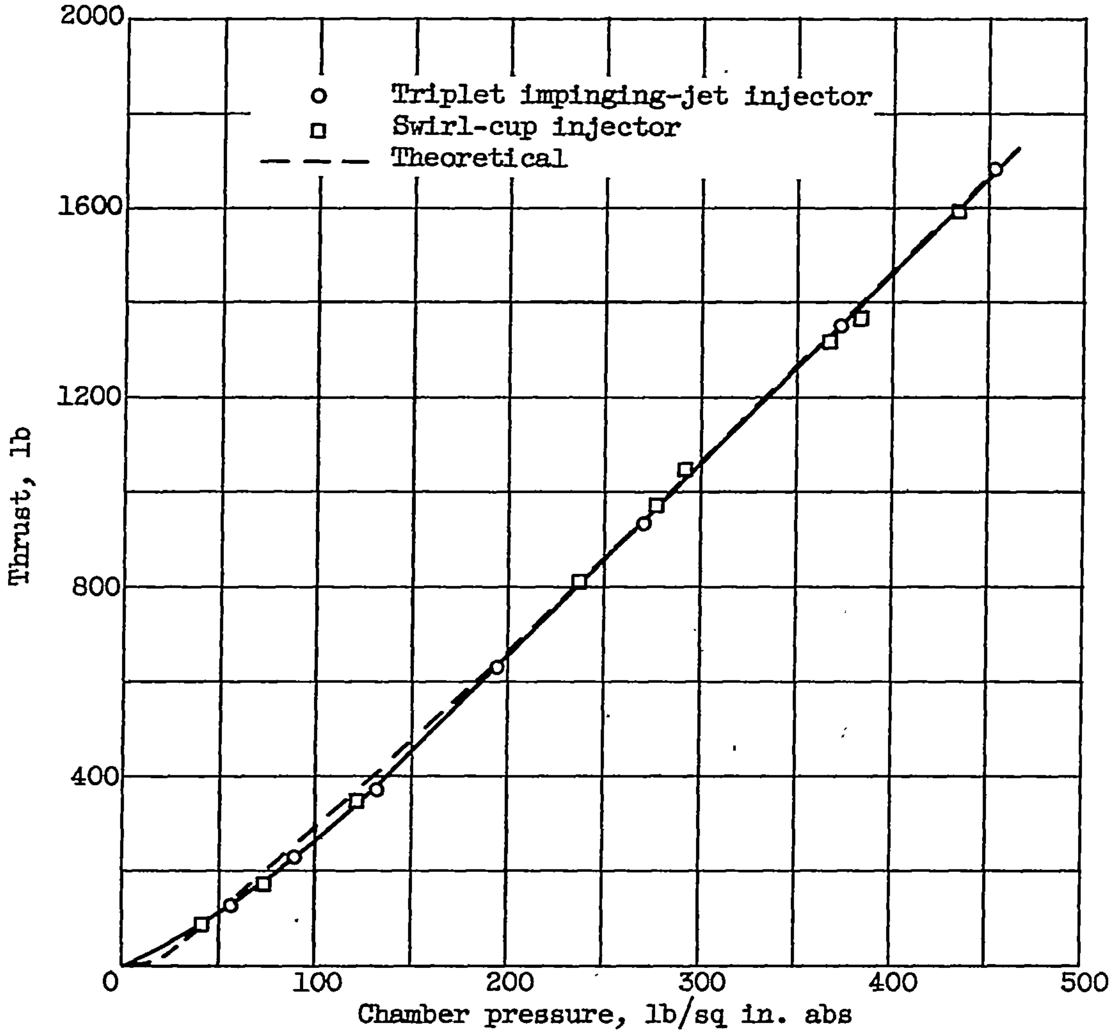

Figure 8. - Thrust as a function of chamber pressure for two variable-thrust injectors using mixed oxides of nitrogen and ammonia.

NACA - Langley Field, Va.